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Long-Term Changes in the Solar Photosphere Associated with Changes in the Coronal Source Flux

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Abstract. Using sunspot observations from Greenwich and Mount Wilson, we show that the latitudinal spread of sunspot groups has increased since 1874, in a manner that closely mirrors the long-term (~100 year) changes in the coronal source flux, F_s, as inferred from geomagnetic activity. This latitude spread is shown to be well correlated with the flux emergence rate required by the model of the coronal source flux variation by *Solanki et al.* [2000]. The time constant for the decay of this open flux is found to be 3.6±0.8 years. Using this value, and quantifying the photospheric flux emergence rate using the latitudinal spread of sunspot groups, the model reproduces the observed coronal source flux variation. The ratio of the 100-year drift to the solar cycle amplitude for the flux emergence rate is found to be half of the same ratio for F_s.

Introduction

The coronal source surface lies at a heliocentric distance near 2.5 solar radii ($r \approx 2.5R_s$) and is where the solar magnetic field is approximately radial. Magnetic flux emerges though the photosphere ($r = 1R_s$) in active regions and the field line loops rise up through the corona as the opposite polarity footprints separate in the differential photospheric rotation; thus flux emerges through the coronal source surface [*Wang et al.*, 2000a]. The total open magnetic flux entering the heliosphere by threading this surface is called the coronal source flux, F_s. *Lockwood et al.* [1999a] have developed a method for estimating annual means of this open flux from observations of geomagnetic activity. The method can be applied to data from 1868 to the present day and has been successfully tested against independent data on the interplanetary magnetic field by *Lockwood and Stamper* [1999]. In addition, *Lockwood* [2001] has shown that cosmic ray fluxes, as determined from neutron monitors, ionisation chambers and the abundance of the ^{10}Be isotope in ice sheets, are highly anti-correlated with these F_s estimates. This is consistent with the magnetic field being the dominant part of the shield that reduces cosmic ray fluxes in the inner heliosphere. The most striking feature of the results presented by *Lockwood et al.* [1999a] is the upward drift in the coronal source flux, superposed on the 11-year solar cycle oscillations, such that the average has increased by a factor of 2.4 since 1900. This variation in F_s has recently been modelled by *Solanki et al.* [2000], using a semi-empirical function of sunspot number to quantify the rate of flux emergence through the photosphere, and using a linear law governing the loss of open flux.

Lockwood and Stamper [1999] noted a correlation between F_s and the total solar irradiance I_s. They found that extrapolation using the best-fit regression gave a reconstruction of the long-term variation in I_s that is very similar to those proposed by *Lean et al.* [1995] and *Solanki and Fligge* [1998], and even more similar to the recently revised reconstruction by *Lean* [2000]. However, as pointed out by *Wang et al.* [2000a], F_s relates to the poloidal field at $r \approx 2.5R_s$ and the implications for the strength and/or structure of the much larger toroidal field at $r = 1R_s$ are not apparent, the field at the solar surface being the most relevant to I_s [*Fligge et al.*, 1998]. *Lockwood et al.* [1999b] noted that peak and average sunspot numbers were highly correlated with cycle averages of F_s. *Pulkkinen et al.* [1999] have reported long-term changes in the average heliographic latitudes of sunspots. In this paper, we present evidence from the sunspot group records of another long-term change in the photosphere that correlates highly with the changes in F_s, namely the spread of sunspot latitudes: we also show that these changes are consistent with the modelling of the F_s variation by *Solanki et al.* [2000].

Comparison of Photospheric and Coronal Changes

We employ the observations of sunspot groups that were made at Greenwich between 1874 and 1981 and we extend this sequence using the observations made in a compatible

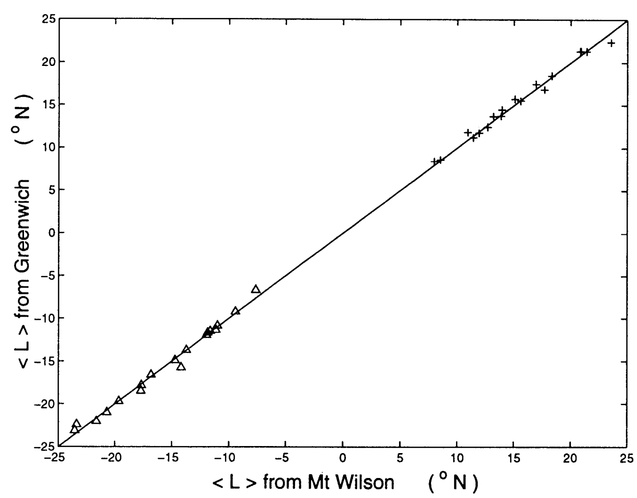

Figure 1. Comparison of the annual means of sunspot group latitudes $< L >$, as observed at Greenwich and Mt. Wilson between 1967 and 1981 in the northern (crosses) and southern (triangles) solar hemispheres. The solid line is the best-fit linear regression.

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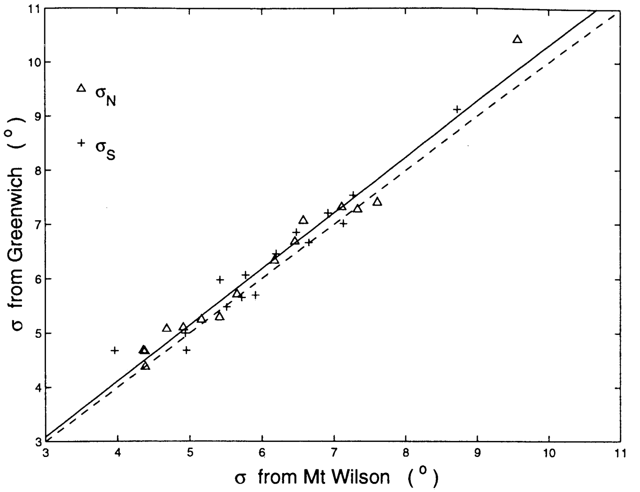

Figure 2. Comparison of the annual standard deviations of the sunspot group latitudes, as observed at Greenwich and Mt. Wilson between 1967 and 1981 in the northern (σ_N , triangles) and the southern (σ_S , crosses) solar hemispheres. The solid line is the best-fit linear regression.

way at Mt. Wilson after 1967. In particular, we employ the daily records of the heliographic latitude L of each sunspot group. For each calendar year, the average $< L >$ and its standard deviation σ were computed. Values were weighted by the group lifetimes by including each group once for each day on which it was observed. Figure 1 compares the mean values $< L >$ obtained from the Greenwich data with those from Mt Wilson for the period 1967-1981, for which both sets of data are available. It can be seen that there is excellent agreement between the two. These observations form the well-known "butterfly" pattern, with the first spots of a new cycle appearing at higher $|L|$ in both hemispheres and $<|L|>$ subsequently falling as the cycle progresses. For most solar cycles, there are one or two years near sunspot minimum when the new (high-latitude) bands of sunspots and the old (low-latitude) bands are both present at the same time. In such cases, the mean latitude and its standard deviation were evaluated for both bands separately and the standard

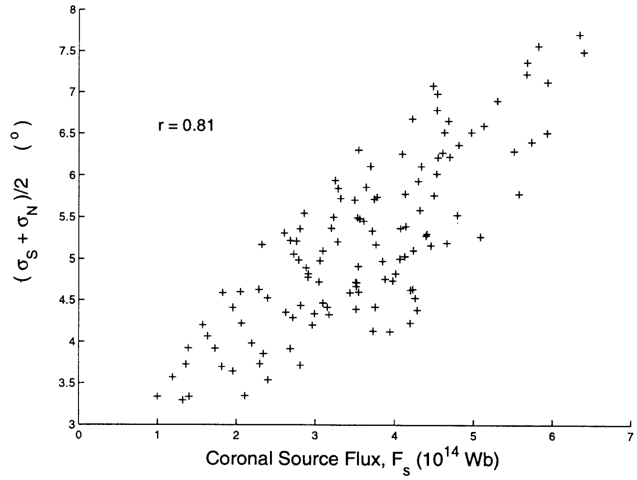

Figure 4. Scatter plot of annual means of the coronal source flux, F_s , and of the standard deviations of sunspot group latitudes, $(\sigma_N+\sigma_S)/2$.

deviations in each hemisphere were combined as the square root of the sum of the squares.

The standard deviations are a measure of how spread over the photosphere the sunspots groups are. Figure 2 shows that the inter-calibration of the σ values from Greenwich and Mt. Wilson for 1967-1981 is not quite as straightforward as for $<L>$. The standard deviations in the northern and southern hemispheres, σ_N and σ_S respectively, are plotted as crosses and triangles. The data from the two observatories agree closely (the correlation coefficient is 0.98). However, there is a systematic tendency for Mt Wilson estimates of σ to be slightly lower than those from Greenwich. This can be seen in figure 2: the best-fit linear regression (solid line) lies slightly above the dashed line, on which all points would sit if the two data sets were identical. From figure 2, σ_N and σ_S values from Mt Wilson can be multiplied by a factor of 1.03 to make them compatible with the Greenwich data.

The good agreement obtained by using this inter-calibration factor allows us to append the Mt. Wilson data for

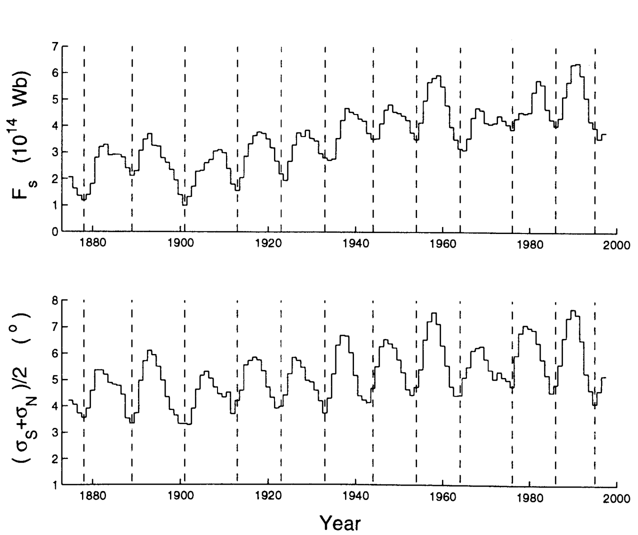

Figure 3. (a) The variation of annual means of the coronal source flux, F_s , as estimated from geomagnetic activity using the method of *Lockwood et al.* [1999a]. (b) The average of the standard deviations of sunspot group latitudes, $(\sigma_N+\sigma_S)/2$.

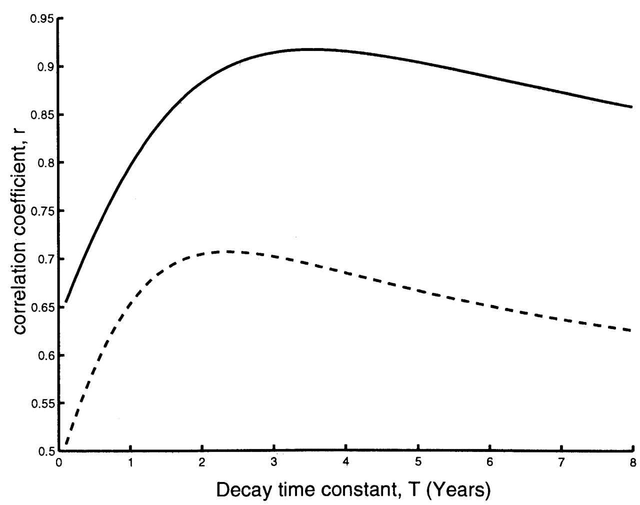

Figure 5. The correlation coefficient between the flux emergence rate $E = \{dF_s/dt + F_s/T\}$ and the mean of the standard deviations of sunspot group latitudes $(\sigma_N+\sigma_S)/2$, as a function of the flux decay time constant, T. The dashed line is for unsmoothed data, the solid line for 3-year running means.

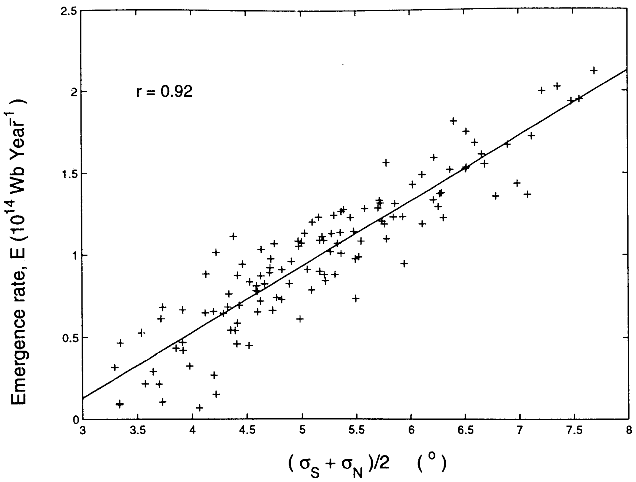

Figure 6. Scatter plot of the flux emergence rate through the coronal source surface, $E = \{dF_s/dt + F_s/T\}$ and the mean of the standard deviations of sunspot group latitudes $(\sigma_N+\sigma_S)/2$, for the best-fit flux decay time constant, $T = 3.6$ years (see figure 5). The solid line is the best-fit linear regression.

after 1981 to the Greenwich data and obtain a homogeneous data set for 1874-1999. The bottom panel of figure 3 shows the average of the northern and southern hemisphere standard deviations, $(\sigma_N+\sigma_S)/2$. The top panel shows the corresponding annual values of the coronal source flux F_s, as derived by *Lockwood et al.* [1999a]. The vertical dashed lines are the times of sunspot minima. The two variations show a great many similarities (in their averages as well as their maxima and minima). Both show a solar cycle oscillation superposed on a general upward trend, interrupted by brief falls around 1900 and 1960. Peaks in $(\sigma_N+\sigma_S)/2$ vary in a similar way to those in R, but the minima show a clear rise, whereas R falls to very small values in each minimum. The ratio of the solar cycle amplitude to the magnitude of the long–term drift is different: for F_s, the amplitude of the variation during cycle 22 (1986-1995) is 2.38×10^{14} Wb; whereas the average for the whole of cycle 22 is larger than that for cycle 14 (1901-1913) by 2.89×10^{14} Wb. The corresponding values for $(\sigma_N+\sigma_S)/2$ are 2.99° and 1.69°. Thus the ratio of the long-term drift (since 1900) to the recent solar cycle amplitude is roughly 1.2 for F_s, but is only about 0.6 for $(\sigma_N+\sigma_S)/2$. This difference gives rise to the scatter in figure 4, which shows $(\sigma_N+\sigma_S)/2$ as a function of the lagged F_s ; nevertheless a correlation is evident (the peak correlation coefficient is 0.81 at a lag of 0.5 yr, falling to 0.63 for simultaneous data).

The Flux Emergence Rate

Solanki et al. [2000] have obtained an excellent match to the variation of F_s derived by *Lockwood et al.* [1999]. The key equation in their model is that of continuity of open flux:

$$dF_s/dt = E - F_s/T \qquad (1)$$

where T is the time constant for destruction of open flux and E is the rate of its emergence through the coronal source surface. Solanki et al. equate E to γE_p, where E_p is the rate of flux emergence through the photospheric active regions and $\gamma = (1+\tau_t/\tau_a)^{-1}$ and thus depends on the time constants for flux annihilation in active regions (τ_a) and for transfer of flux from active regions to the network (τ_t). Solanki et al. estimate γ to be 0.015 and derive a best fit with a time constant T of 4 years. Because we know F_s and dF_s/dt from the work of *Lockwood et al.* [1999], we can use equation (1) to compute the flux emergence rate E for an assumed value of T. Solanki et al. estimate E_p from R, but need to allow for the fact that only a small part of the flux emerges from sunspots (total area A_s), and a much larger part emerges as small flux tubes from active region faculae (total area A_f) . Thus they multiply R by an area factor (which varies with the solar cycle) to give E_p proportional to $(1+ A_f/A_s)R$. Solanki et al. then use an empirical hyperbolic relationship for (A_f/A_s) that allows E_p to be computed from R. Because $(\sigma_N+\sigma_S)/2$ quamtifies the latitudinal spread of active regions, and thus is related to (A_f+A_s), and has a similar solar cycle variation to (R/A_s), suggests that $(\sigma_N+\sigma_S)/2$ could be an indicator of E_p. This idea is investigated in figure 5, which plots the correlation coefficient between $(\sigma_N+\sigma_S)/2$ and $E = \{dF_s/dt + F_s/T\}$, as a function of the flux decay time constant, T. The dashed line is for the annual means, but because relatively large fluctuations are introduced in taking the temporal gradient of F_s, three-point running means give the higher correlations shown by the solid curve. The peak correlation coefficient is 0.92 at $T = 3.6$ yr, which is close to the estimate of 4 years obtained by Solanki et al. Using a Fischer-Z test, we find the correlation coefficient is significantly different (at the 95% level) from its peak value at $T \leq 2.8$ yr and $T \geq 4.5$ yr and this defines an uncertainty in the best T estimate as ±0.8 yr. The unsmoothed data give $T = 2.6\pm1.2$ yr which is lower, but still consistent within the uncertainties. Figure 6 shows the scatter plot of the 3-point running means of $\{dF_s/dt + F_s/T\}$ and $(\sigma_N+\sigma_S)/2$, for the optimum decay time constant of $T = 3.6$ yr, as defined by figure 5. The solid line is the best-fit linear regression. This fit is used to predict the variation of the flux emergence rate E from the observed $(\sigma_N+\sigma_S)/2$. The result is the solid line in figure 7 which compares very well with the variation computed from F_s (dot-dash line).

As a test of these estimates of E, derived from the spread of sunspot latitudes, we can use them, along with the best-fit T of 3.6 years, as input into equation (1) to model the variation of F_s. The calculations are started from an initial value and we here use the observed value for 1874. The results are shown in

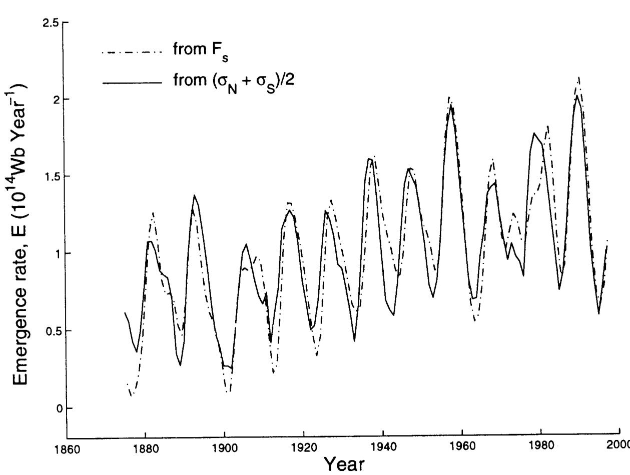

Figure 7. The variations of the emergence rate E computed from F_s (dot-dash line, $E = \{dF_s/dt + F_s/T\}$) and from the mean of the standard deviations of sunspot group latitudes $(\sigma_N+\sigma_S)/2$, using the regression fit shown in figure 6 (solid line). The best-fit flux decay time constant of $T = 3.6$ years is used (see figure 5).

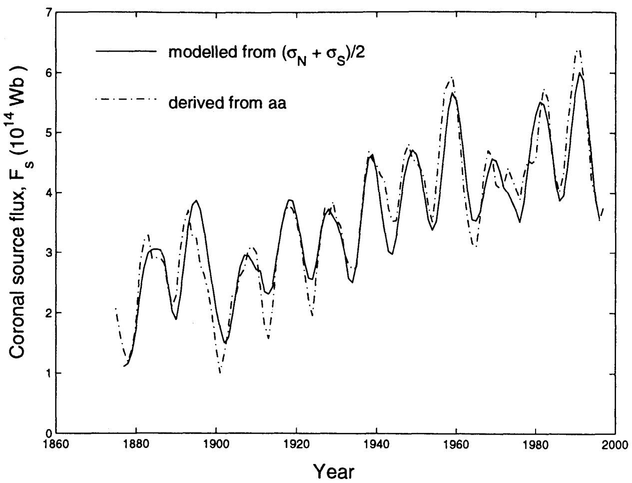

Figure 8. The variations of the coronal source flux F_s, as derived from geomagnetic activity by *Lockwood et al.* [1999a] (dot-dash line), and as modelled using the best-fit variation of emergence rate E shown in figure 7 (solid line) for the best-fit flux decay time constant of $T = 3.6$ years.

figure 8. The model predictions (solid line) are insensitive to T over its most probable range (2.6-4.5 yr.) and are very close match to the values observed by Lockwood et al. (dot-dash line) and, in general, both the solar cycle variation and the long-term drift are reproduced.

Discussion and Conclusions

Lockwood et al. [1999b] noted that both the peaks of the sunspot numbers and their solar cycle averages were highly correlated with the cycle averages of the coronal source flux, F_s, as estimated by *Lockwood et al.* [1999a]. In this paper, we have shown that there are also changes in the spread of sunspot group latitudes that are highly correlated with F_s. Furthermore, this spread appears to be a good proxy for the flux emergence rate through the coronal source surface, supporting the argument of *Solanki et al.* [2000] that the emergence rates through the photosphere and the source surface are, to first order, linearly related. Solanki et al. computed emergence rates using a complex function of sunspot numbers – we here show a simple estimate of the spread of sunspot latitudes produces an equally good fit to the coronal source flux variation. We find the time constant for the loss of open flux is 3.6±0.8 years. This is also consistent with the semi-empirical modelling by Solanki et al. and with the numerical model of *Wang et al.* [2000b], although the latter is for the flux emerged via a single active region with a different γ, and not for the whole sun.

Measurements of the total solar irradiance, I_s , have revealed a solar cycle variation of about 0.1% [*Fröhlich and Lean*, 1998]. However, the crucial factor for climate change studies, namely the ratio of the long-term (~100 year) drift to the solar cycle variation, is not known with any certainty. We here show that this ratio for the latitude spread of sunspot groups (and thus for the inferred photospheric flux emergence rate, E_p) is about half of the same ratio for the coronal source flux. As a result, were it valid to use E_p as a proxy for I_s , this would give a long-term drift in irradiance that is half that obtained by extrapolation based on F_s by *Lockwood and Stamper* [1999] (and which agreed well with the reconstructions by *Lean et al* [1995], *Solanki and Fligge* [1998a] and *Lean* [2000]). The data presented here show that there are long-term changes in the solar photosphere that are similar to the changes in the coronal source flux, as inferred from geomagnetic activity. A major challenge now is to investigate if these are related to irradiance changes.

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